WP2 – Transverse impedance and stability

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HL-LHC Collaboration Meeting, Vancouver, Canada – 20/04/2023

WP2 – Transverse impedance and stability

- Introduction & context
- Review of impedance studies & model updates
- Overview of machine development (MD) studies during Run 3
- Transverse stability situation

Context

- Transverse impedance is a source of bunch intensity limitations in the current LHC machine at top energy.
- One of the main contributions: collimators
  - very close to the beam
  - initially, all primaries (TCPs) and secondaries (TCSs) were in CFC (poorly conductive material) ⟶ large resistive-wall impedance
  - also significant geometric impedance (tapers)

  ⟶ partial upgrade of TCPs and TCSs during LS2 (MoGr, Mo-coated for TCS), more to come in LS3.
- Most critical part of the cycle: flat top
  - after ramp (collimators are closed), just before collapsing beam separation (which provides large beam-beam tune spread, hence large Landau damping)

  ⟶ only octupoles provide the required Landau damping at flat top.

Impedance studies

- Some impedance contributions reviewed:
  - Beam Gas Vertex: impedance studied (input to BGI/BGV review – see ***L. Giacomel, H. Guérin & I. Karpov***, *209th WP2 meeting, 18/10/2022*)

    ⟶ impedance is acceptable – but BGV not in baseline anymore (following BGV/BGI review)
  - Beam-beam Long-Range Wire Compensator: preliminary studies (see ***B. Salvant***, *WP2/WP13 HL-LHC Satellite Meeting, 23/09/2022*)

    → Impedance significant but no showstopper
  - Vacuum valves between TCLMB mask and Q4: studies done (see ***L. Giacomel***, *215th WP2 meeting*, 20/06/2023)

    → Impedance increase not acceptable

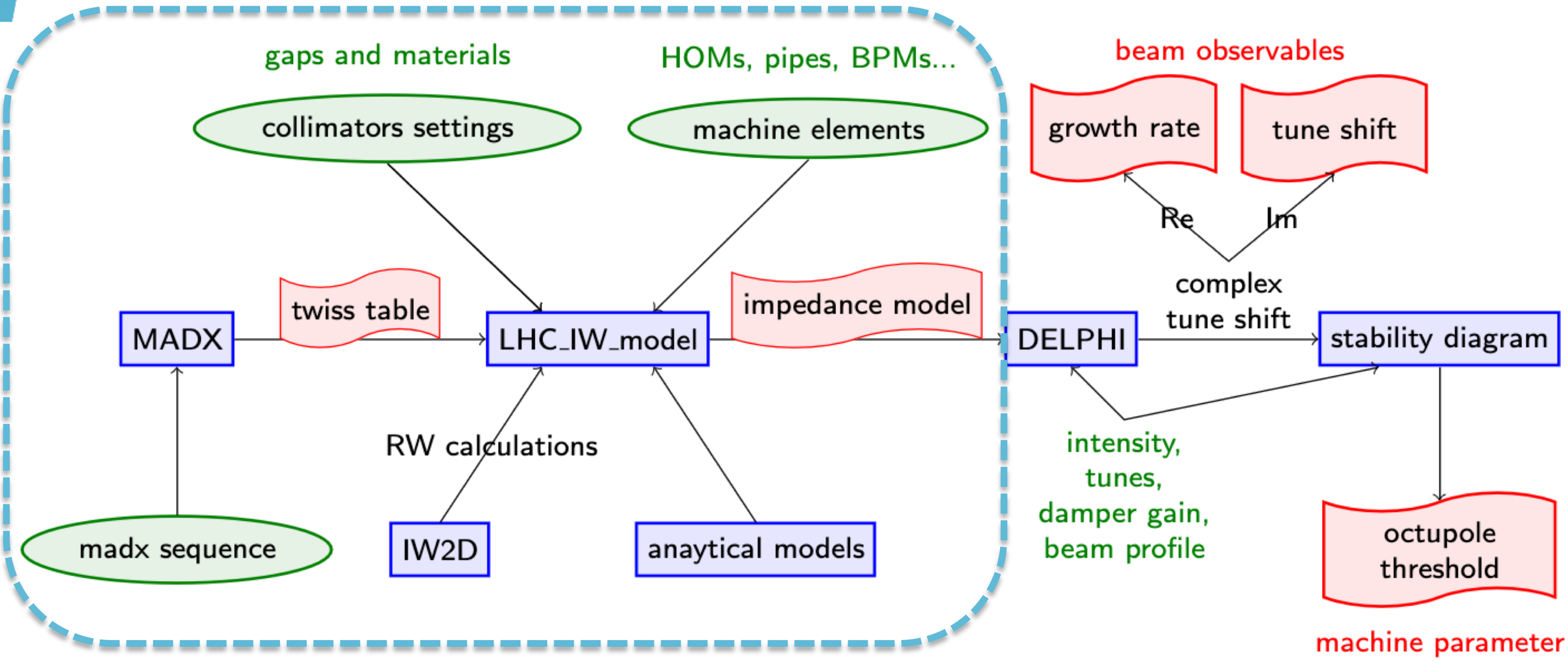
    → New manual FRAS table decided, to avoid aperture change and cavity-like structure
  - Absence of Cu coating in Y-chambers: studies done (see ***L. Giacomel***, *215th WP2 meeting*, 20/06/2023)

    → not fundamental importance, stainless steel can be used.

  Note: geometric impedance was already optimised in the past.

Updated of code infrastructure

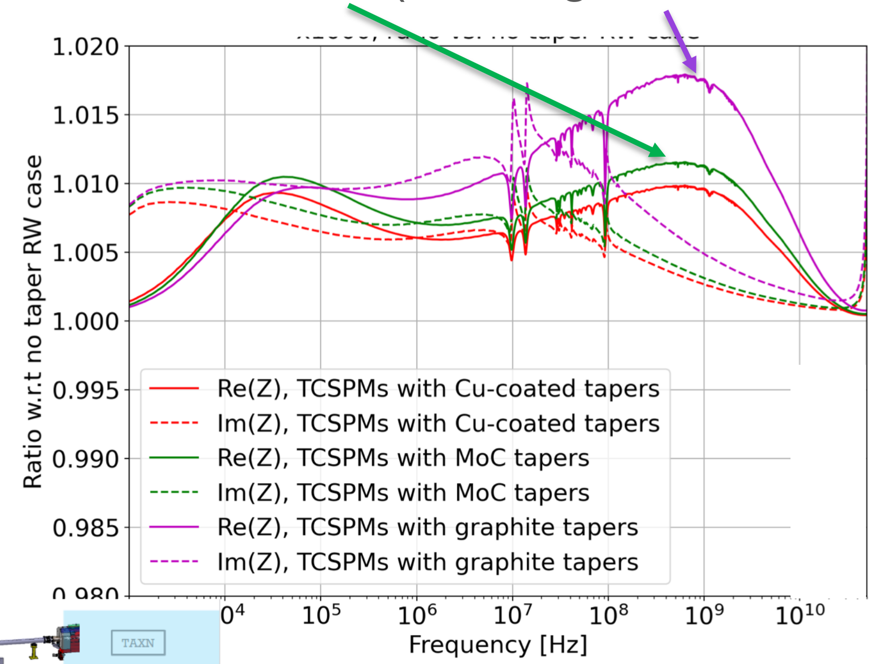
- **Model fully re-implemented using a new code infrastructure: PyWIT** (https://gitlab.cern.ch/IRIS/pywit)

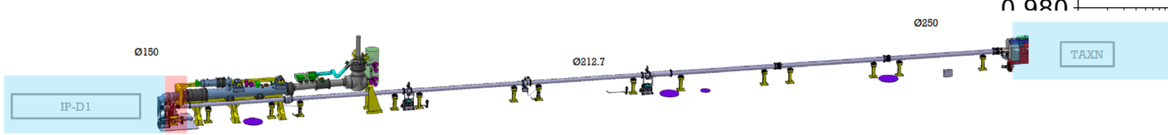


- Lots of code development involved, including on **IW2D** (for resistive-wall).
- LHC/HL-LHC models now in https://gitlab.cern.ch/IRIS/lhc_pywit_model/

Update of impedance model

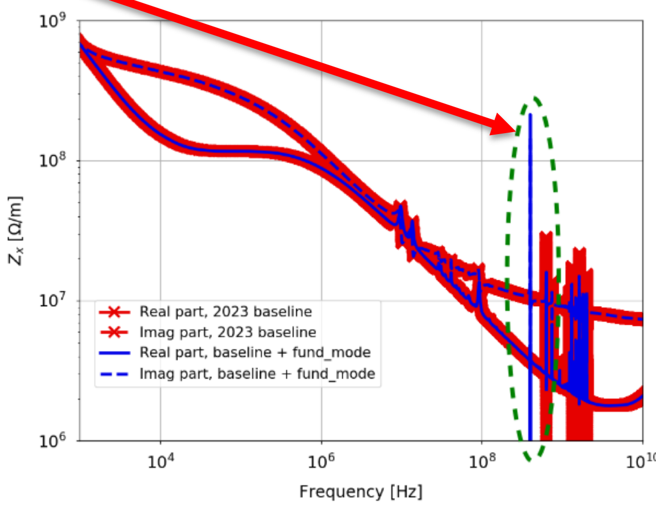
- **Main updates** to impedance model:
  - New collimator materials – mainly Cu-coated graphite TCSPMs but not only – overall impedance decrease by almost **1%**.
  - Resistive-wall effect of collimator tapers (detrimental, but model more accurate) - impedance increase of **~1%** (would get 2% with graphite tapers in TCSPMs
  - Crab cavities fundamental mode (detrimental – see next slides)
  - ~160 m of stainless-steel warm pipe close to the triplets (0.1% impact)





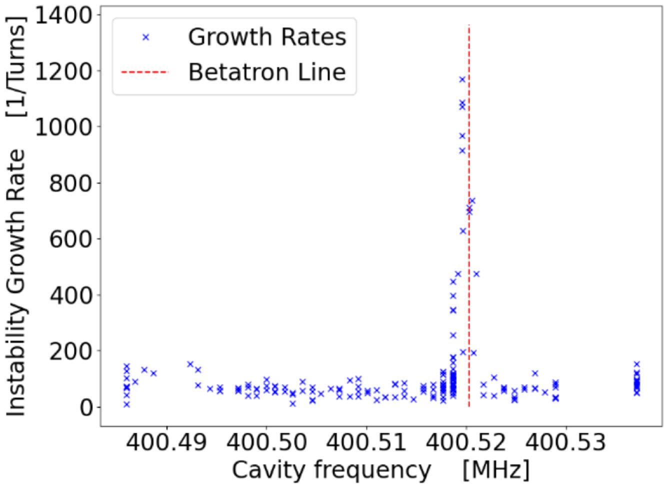
Crab cavities impedance

- Fundamental mode has a strong effect on transverse impedance:



L. Giacomel, *211th WP2 meeting*, *17/01/2023*

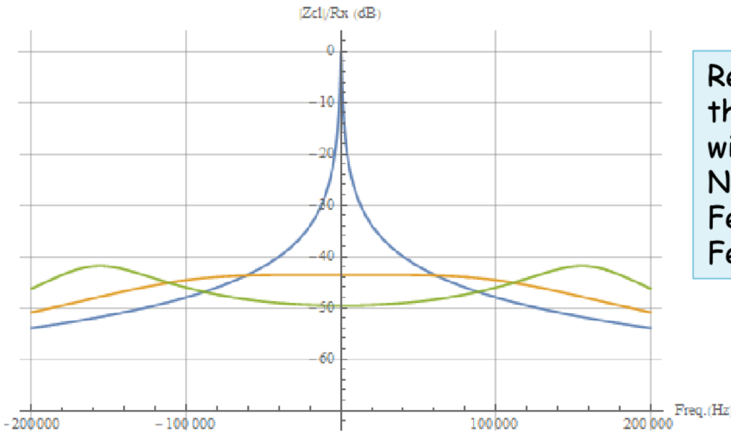
Effect also studied and confirmed in a crab cavity SPS MD:



L. Giacomel, *WP2/WP4 meeting*, *22/11/2022*

Crab cavities: impedance mitigation

- Gain of standard RF feedback cannot be increased further:

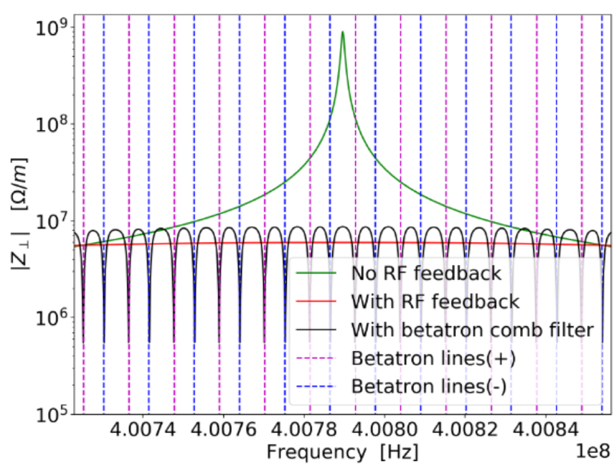


Reduction of the modulus of the transverse impedance with:
No feedback (blue)
Feedback gain=150 (orange)
Feedback gain=300 (green).

***P. Baudrenghien**, [WP2/WP4 meeting](), 22/11/2022*

... but a **comb filter** can reduce impedance effects by acting at the right frequencies (betatron lines):

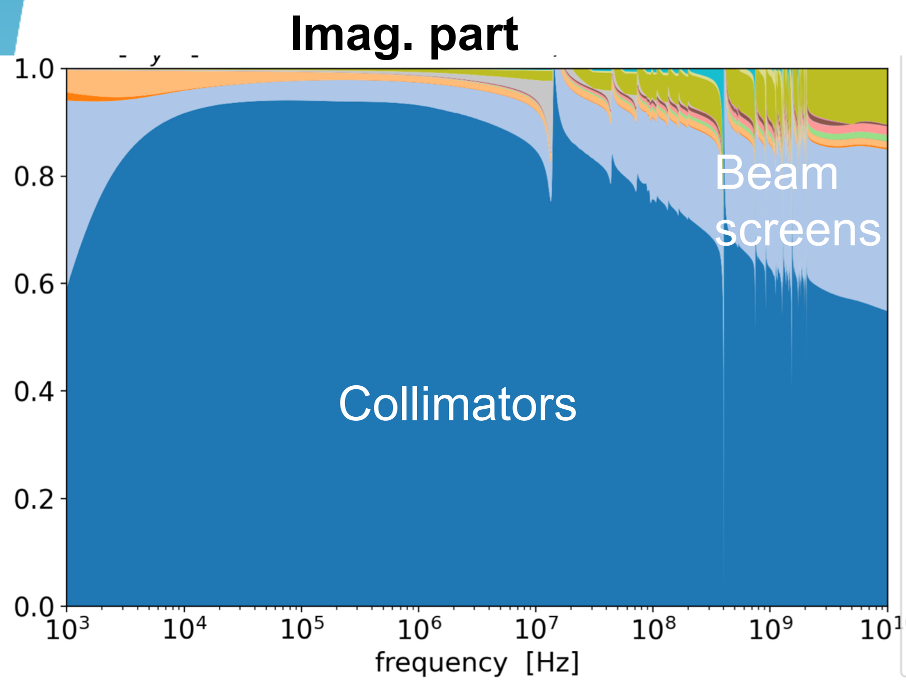
***L. Giacomel**, [WP2/WP4 meeting](), 21/03/2023*

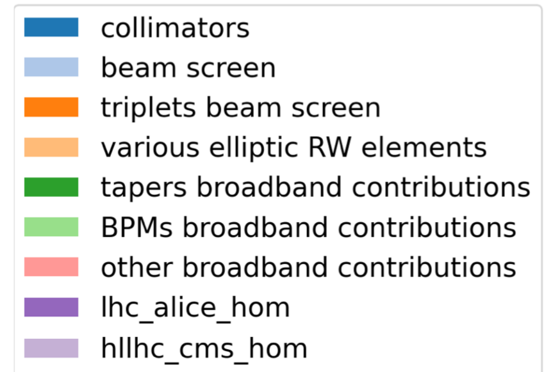


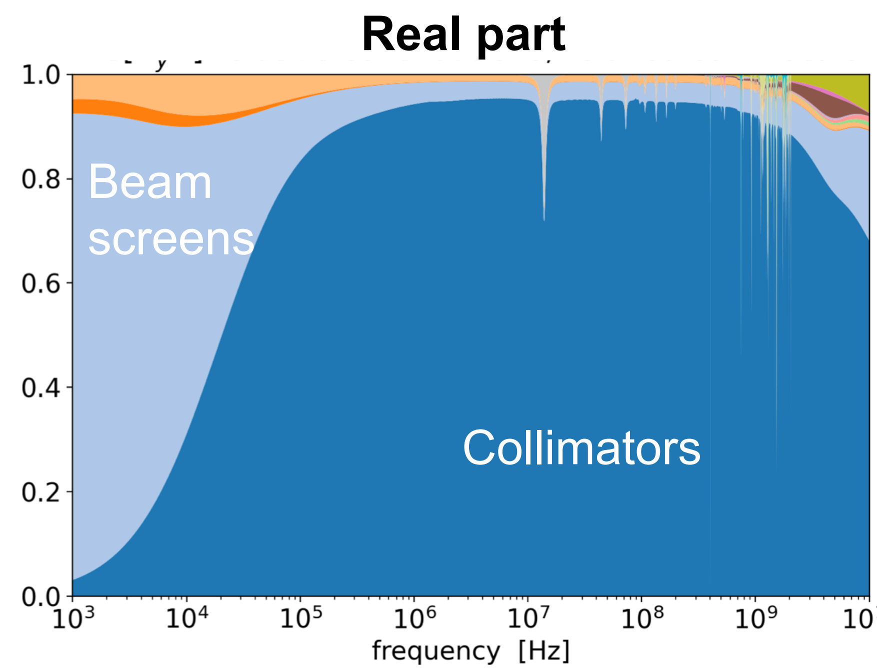
Impact of mode decreases by **an order of magnitude**, **but** assumes tune known within $\pm 5.10^{-3}$
⟹ Still some uncertainty.
⟹ Bunch-by-bunch tune shift MD planned for 2024.
If comb filter is not used, **flat optics** can also reduce the octupole current.

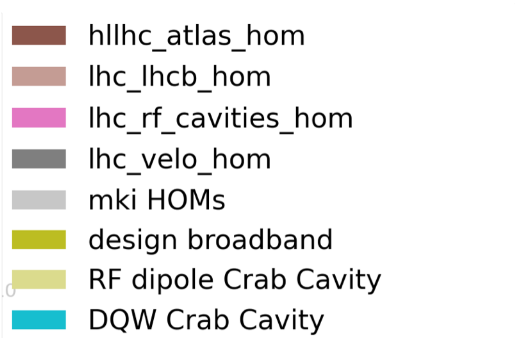
HL-LHC impedance contributions

- Breakdown of all impedance contributions (relaxed collimator settings, vertical plane):





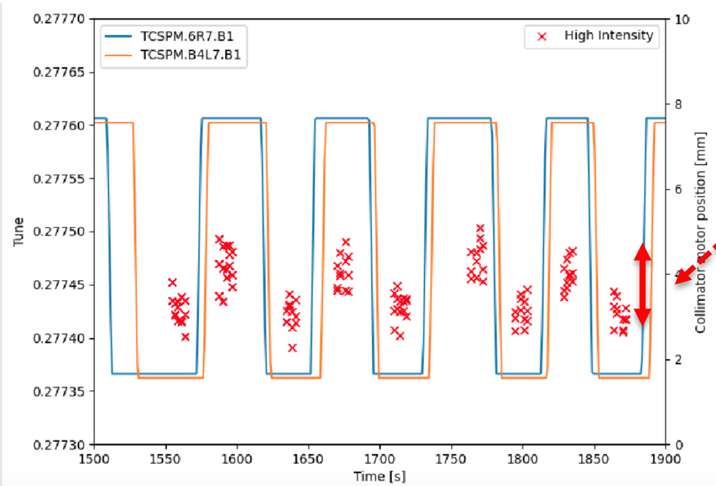




LHC machine development studies

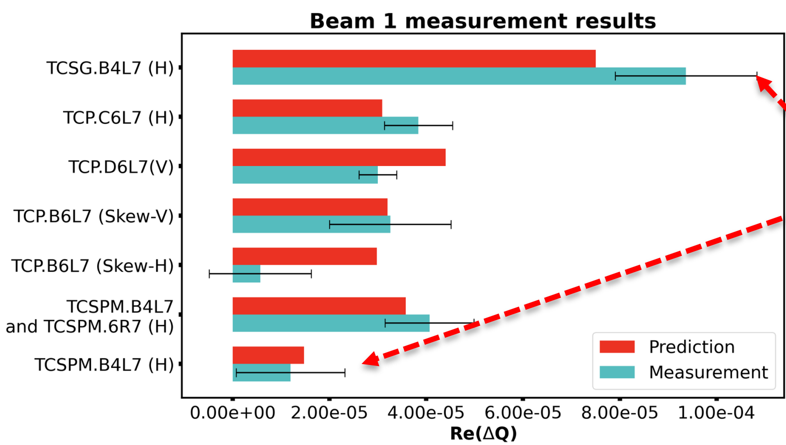
- Tune shift from collimators measured during LHC Run 3:

TCSPM.B4L7.B1 and TCSPM.6R7.B1 :

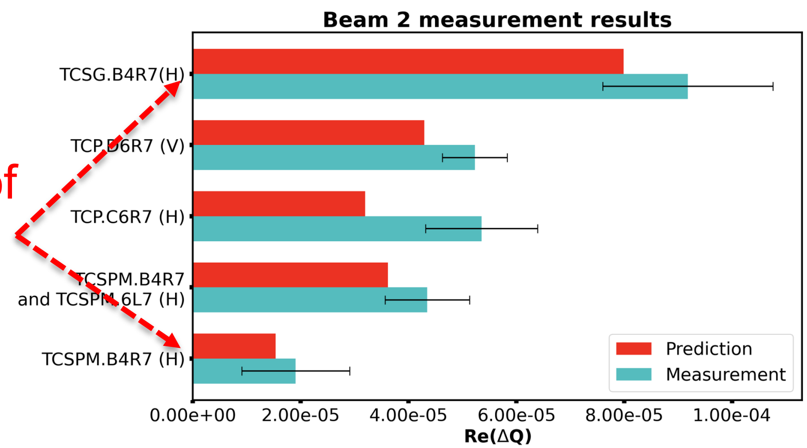


Back-and-forth motion of the jaws to check tune shift from impedance of single collimators

Adnan Kurtulus, ABP-CEI meeting 15/12/2022



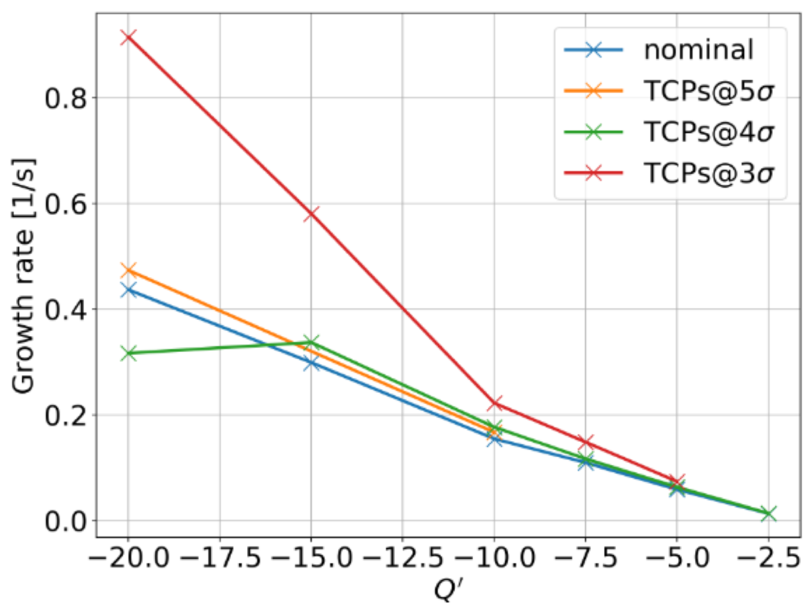
Impact of LS2 upgrade



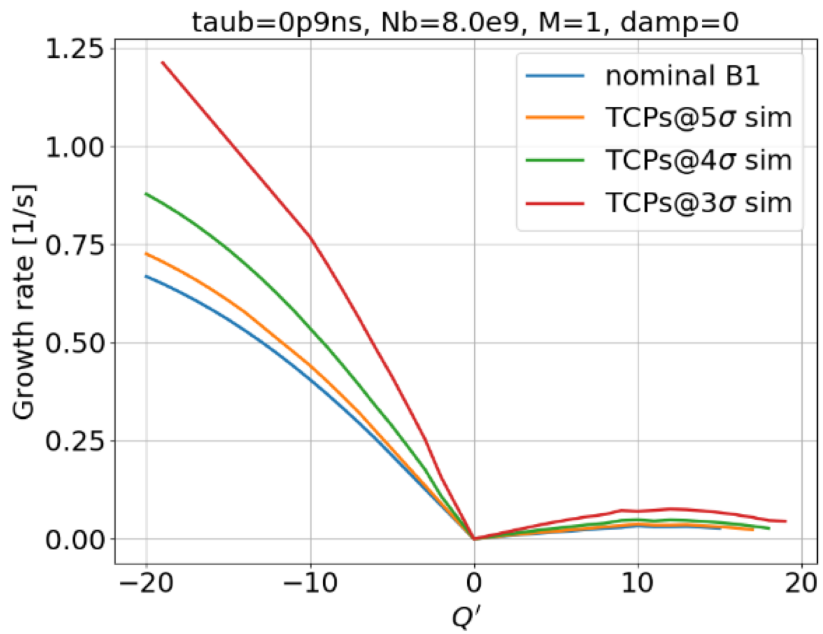
LHC machine development studies

- To probe the real part of the impedance: measurements of instability growth rates at injection

Measurements:



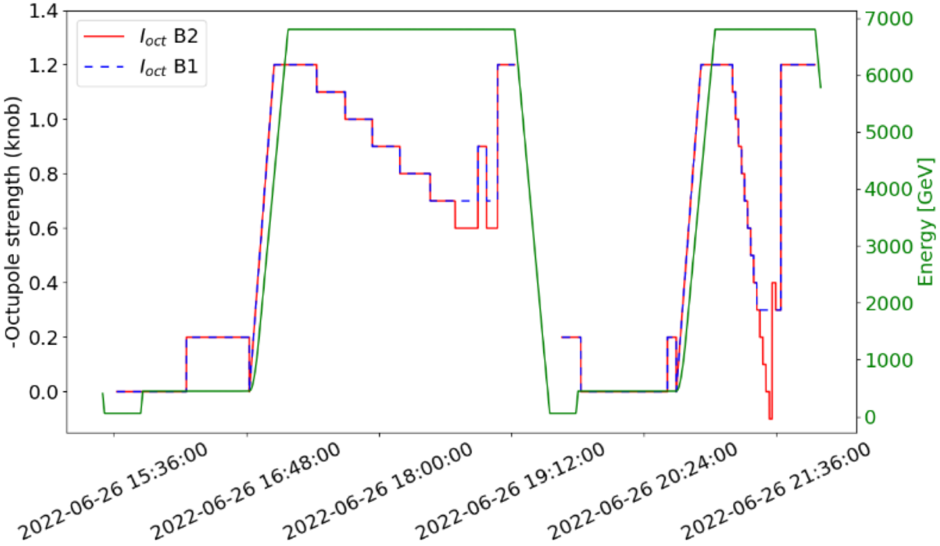
Simulations:



$\Longrightarrow$ As for real tune shifts, relative agreement between measurements & model.

LHC machine development studies

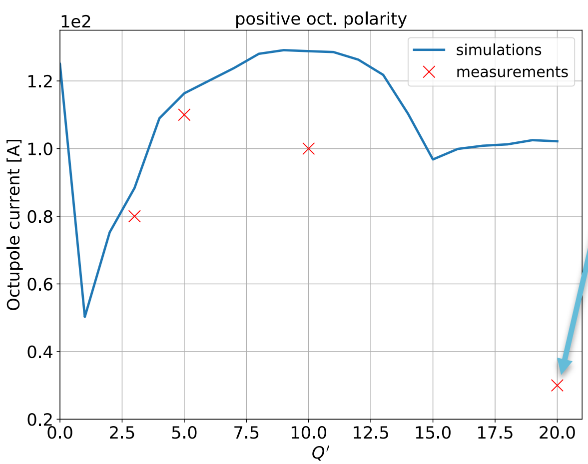
- Stability main quantity of interest: Octupole threshold
  - Latency effect (slow vs fast octupole decrease):

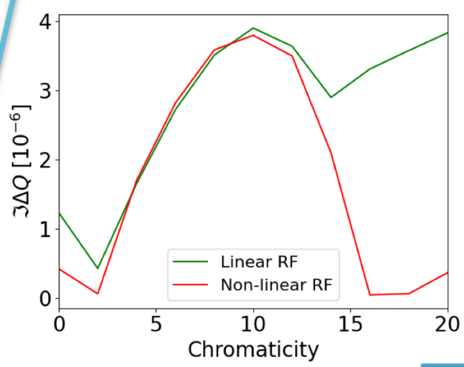


⟹ octupole must be ~twice higher when staying a long time at the same octupole current (*S. Furuseth & X. Buffat*, [Eur. Phys. J. Plus 137, 506, 2022](#))

Subject of intense studies – impact of non-linear bucket

  - Octupole threshold vs Q' (latency not included):

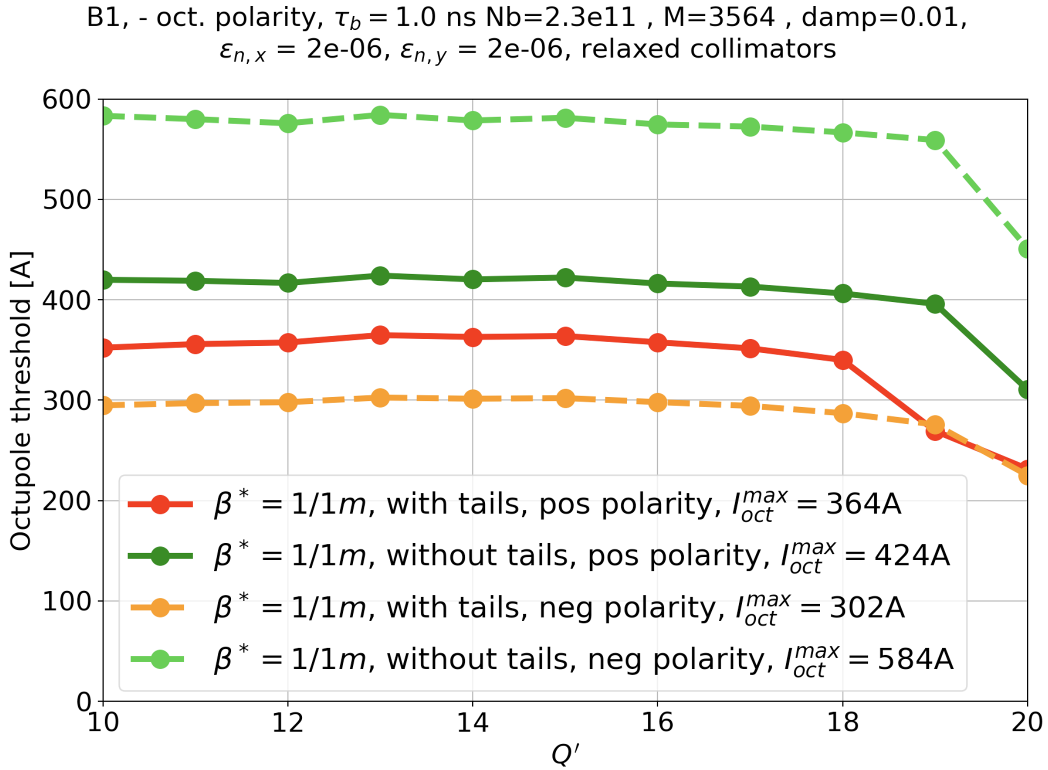




X. Buffat

HL-LHC overall transverse stability

- The model for transverse tails has been reviewed:
  - In the past tails assumed absent (parabolic bunch in transverse, tails cut at 3.2σ) – uncertainties on beam from LHC injectors (after LHC Injector Upgrade – LIU) + HEL
  - Now: LIU beam known to have tails, no HEL ⟶ **Gaussian tails assumed.**
  - It also means that **negative octupole polarity** is back in the game (better stability diagram in principle, but some compensations with long-range beam-beam):

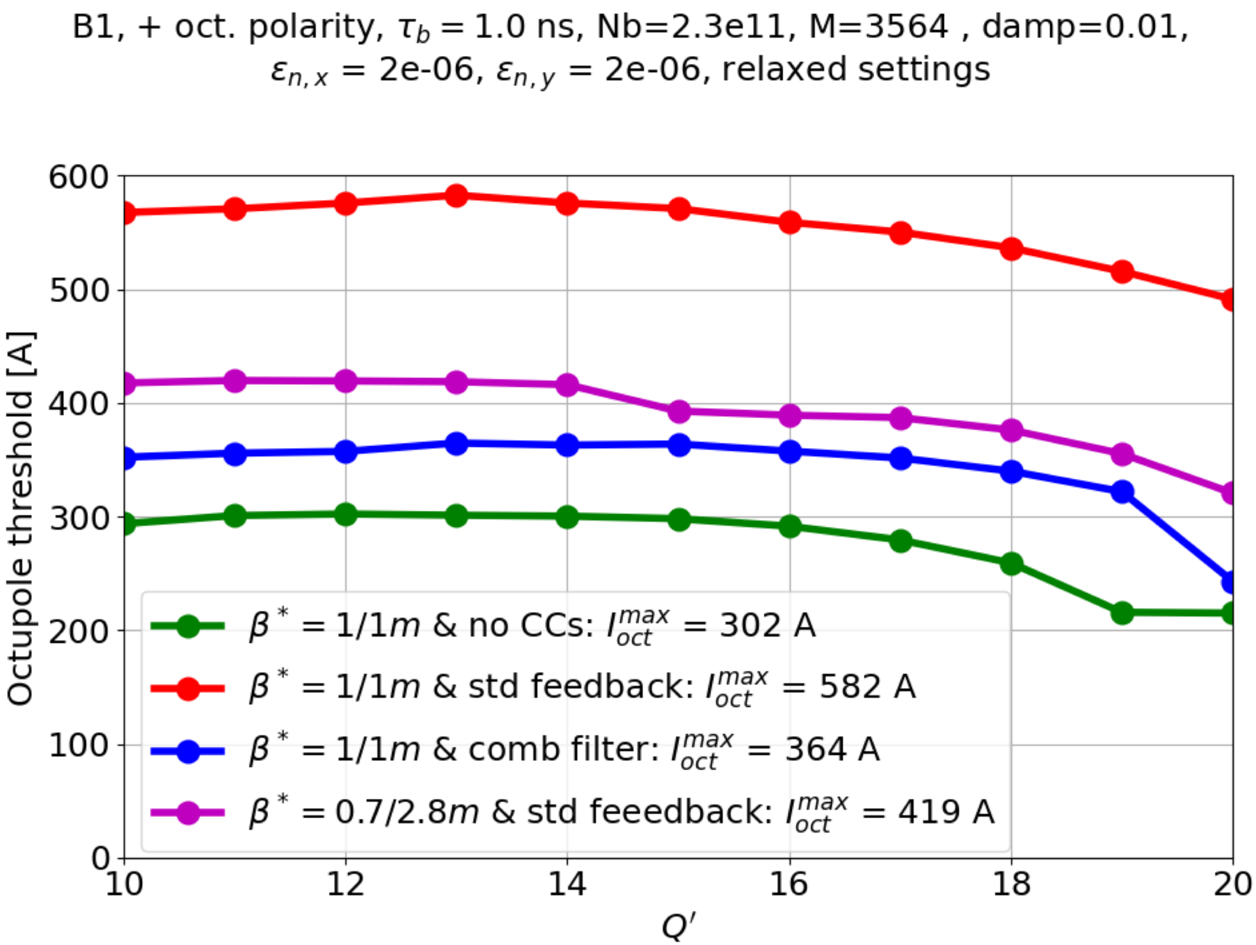


⟹ ~16% improvement with tails
⟹ with tails, negative polarity is better than positive, overall.

Note: here we assume the crab cavities comb filter is used.

HL-LHC overall transverse stability

- Impact of crab cavities fundamental mode and mitigation options:

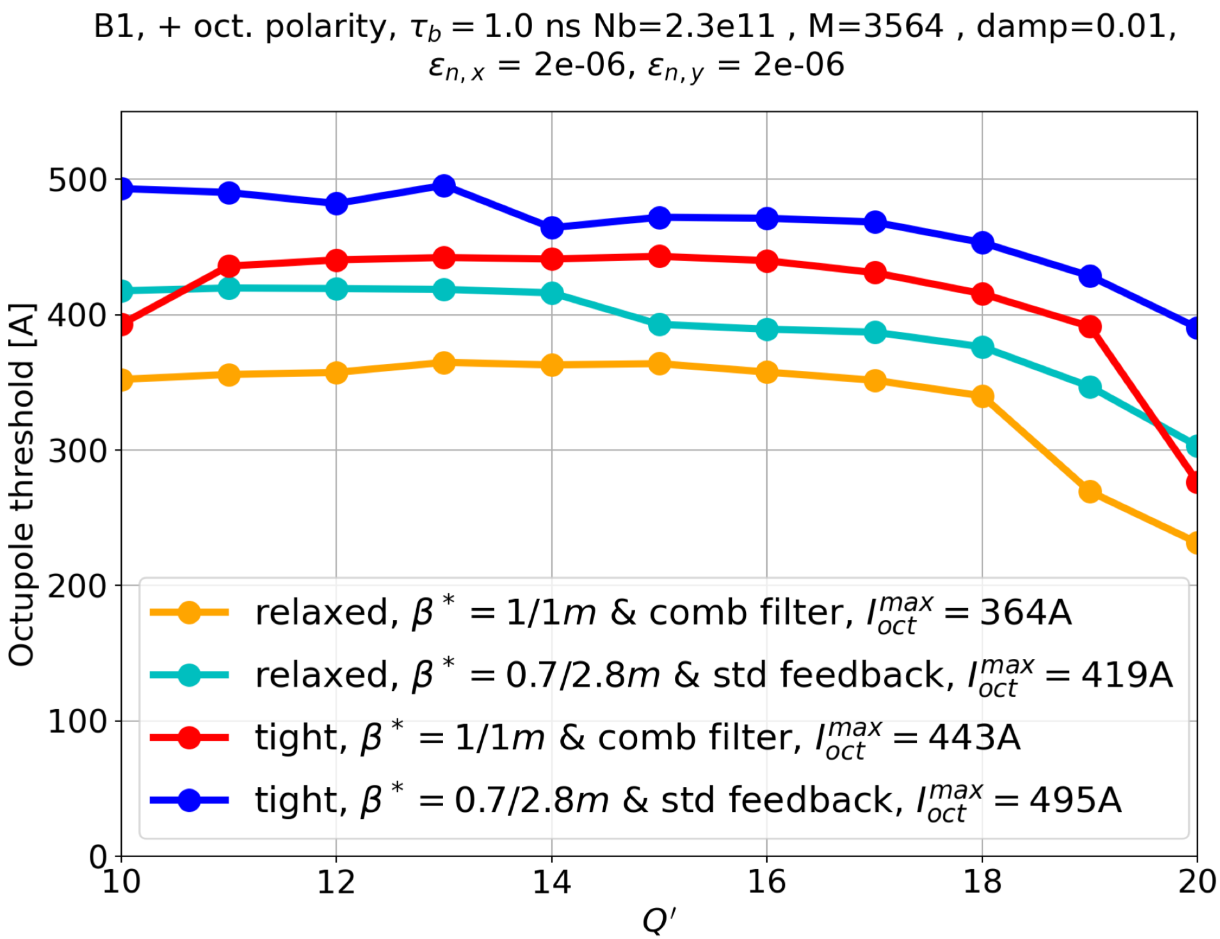


⟹ Without any additional mitigation, huge impact of CCs (+280 A)
⟹ comb filter is the best mitigation (80% reduction)
⟹ std RF feedback with flat optics is a good backup option (60% reduction).

Note: the flat optics case also features a telescopic index (*S. Fartoukh*, PRST-AB, 16, p. 111002, 2013), but we have rescaled the octupole currents to a telescopic index of 1.

HL-LHC overall transverse stability

- Collimator settings were assumed “relaxed” in the latest scenario for run 4 (8.5 σ for TCPs), but tight settings (slightly larger than run 2 & 3 – 6.7 σ in TCPs) are also on the table:



⟹ Tight settings give less stability, but are still manageable
⟹ it also depends on dynamic aperture: large octupole currents might be an issue (see *S. Kostoglou, C. Droin, G. Sterbini*, et al)

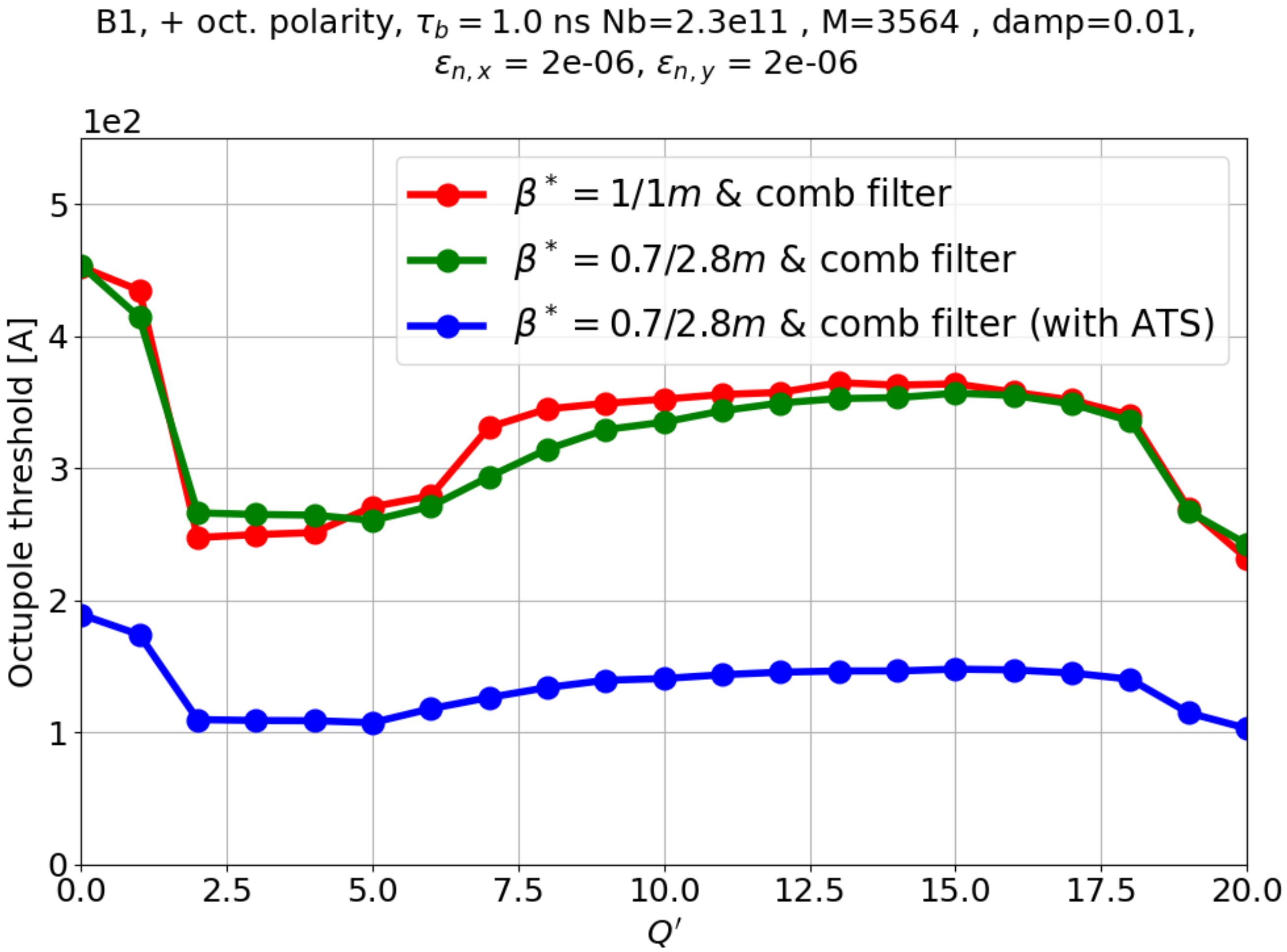
Summary and outlook

- Impedance of HL-LHC received a number of updates, including a complete change of code infrastructure.
- Latest developments on collimators were included (Cu-coated TCSPMs, coated tapers).
- Crab cavity fundamental mode could have a strong impact on stability, but two mitigations were found:
  - Best option: comb filter (still to be tested)
  - Good backup option: RF feedback with flat optics
- LHC MDs provided data on impedance (tune shifts, growth rate, octupole threshold) – in many cases in ~agreement with models
  - in particular, latency effect on Landau damping is confirmed,
  - no degradation observed for new TCSPMs (from e.g. radiation).
- Gaussian tails of the beams from the injectors are clearly beneficial, and put the negative polarity back on the table, for even more stability.
- Studies ongoing to
  - decrease the collimator impedance (IR7 optics, possibly also IR3),
  - understand better the effect of the longitudinal bucket non-linearities,
  - simulate accurately multibunch effects (crab cavities; 8b4e / hybrid filling schemes).

Appendix

HL-LHC overall transverse stability

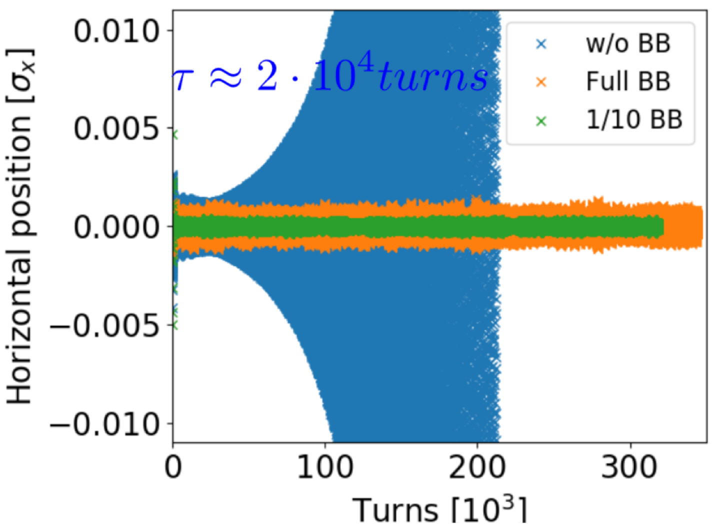
- Impact of optics choice:



Here there is no rescaling of the flat optics case (telescopic index is left unchanged)

Crab cavities: noise & amplitude feedback

- Heavy simulation effort to understand if Landau damping from beam-beam effects sufficient to damp instabilities from **CC amplitude feedback** used to mitigate noise issue (800 MHz demodulation)



Multibunch simulations in collisions with **Xsuite**, including **beam-beam, feedback & impedance effects**
⟹ instability from feedback **stabilized by beam-beam**
… but 400 MHz demodulation preferable (no instability in the first place).

X. Buffat, *WP2/WP4 meeting, 21/03/2023*

- Designing a faster approach to simulate multibunch instabilities: